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DETERMINISTIC STABILITY ANALYSIS FOR PRODUCTION-LINE CONTROL OVER PRIVATE 5G

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ABSTRACT:
Private 5G networks are a requirement for Industry 4.0 automation in synchronized conveyors, AGVs, and robotic assembly lines due to their impressive ultra-reliable low-latency communication. Through the use of network slicing and URLLC, the system is able to achieve a latency of less than 1 ms, 99.9999 percent availability, and minimal jitter. Compared to WiFi, such performance is possible in high-density factories where there is a lot of interference thanks to robust handover mechanisms and CoMP transmission across several TRPs.The present analysis provides an examination of stability amid the aforementioned disruptions such as handovers, congestion, and mobility at high speeds. Through the application of path diversity and HARQ retransmissions, Private 5G has been able to support packet delivery that is very deep integrated with operations technology, thus ensuring a deterministic latency for real-time monitoring and predictive maintenance without desynchronization. The security protocols which are in place like SIM authentication and local data processing effectively prevent cyber threats and at the same time keep the control loop intact.There have been reports of deployments resulting in up to 30 percent productivity increase due to the reduced downtime and 25 percent decrease in maintenance costs with the ability to scale IoT devices up to thousands with no issues. labs tests..

Keywords: Private 5G,Conveyor Control, Stability Analysis,URLLC (Ultra-Reliable Low Latency Communication), TSN Integration (Time-Sensitive Networking Integration)

I. INTRODUCTION

Industry 4.0 is turning production into a smart manufacturing cell that needs a very precise closed-loop control of the entire system consisting of conveyor belts, AGVs, and robotic assembly via real-time PID feedback between the PLCs, sensors, and actuators. One of the key features enabling this transformation is private 5G networks that provide ultra-reliable low-latency communication with a very short end-to-end latency of below 1 ms, availability of 99.9999 percent, and a very-low-jitter signal made possible by dedicated gNB slicing. These characteristics make private 5G outperform Wi-Fi in the case of high-density factories that are heavily impacted by the interference coming from the machinery and human mobility.The traditional wired Ethernet and Wi-Fi networks are not able to support the new demands on the reconfiguration process, which is where AGVs have a speed of over 2 m/s, and the production lines are changed frequently, thus causing unpredictable latency spikes during handovers or congestion. Private 5G technology offers solutions to these problems in the form of comprehensive CoMP transmission across multiple TRPs, the integration of TSN (Time-Sensitive Networking) with IEEE 802.1Qbv, PTP synchronization, and HARQ (Hybrid Automatic Repeat reQuest) retransmissions allowing for deterministic performance even under the Ethernet/IP and PROFINET protocols without the need for custom gateways.In this research paper, the authors propose a method for the analysis of deterministic stability that is based on the control of production lines over a private 5G network, where different types of perturbations such as jitter (1-20 ms), packet loss (0.1-1 percent), handover delays, and clock drift have been injected on the test beds of Nokia AirScale with Omron PLCs and Siemens motors. The RMSE, Nyquist margins, and settling times are some of the metrics used to quantify resilience indicating less than 4 percent degradation compared to Wi-Fi baselines, 30 percent productivity gains, and ISO 60204 safety compliance. The results provide the basis for defining thresholds for the deployment of fault-tolerant Industry 4.0 operations

II. LITERATURE SURVEY

Private 5G networks are the key enabler of the Industry 4.0 through ultra-reliable low-latency communication (URLLC), with 1 ms end-to-end latency and 1e-5 packet error rates being the requirements for quality motion control, process automation, and remote monitoring in the production lines. Various wide-ranging surveys underline URLLC outpacing the limitations of both WiFi and wired Ethernet, thus enabling wire-free robot cells and

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conveyor synchronization through TSN integration and gNB slicing. Nokia and Raemis 5G cores performance benchmarks indicate the ultra-low latency of less than 5 ms for multi-link PLC communications, reaching the reliability level of 99.9999 percent under industrial conditions. In the case of Ericsson, the 5G URLLC pilots have been transporting PROFINET RT and PROFIsafe, allowing the instant safety stops in dynamically changing factories that were previously limited by cabling. The edge-powered private deployments for the control of the robots have been endorsed by Qualcomm, who mention the usage of path diversity and CoMP as the strategic solution against the multipath fading caused by the machinery. The studies in numerology reveal that larger subcarrier spacings result in the minimization of delay in the area of line-of-sight but on the contrary cause degradation in the case of a non-line-of-sight factory scenario with metallic obstructions. The ITU has been working on the transition to beyond-5G URLLC through the use of Finnish and Korean testbeds, which are able to support group multicast for deterministic control with cycle times of under 4 ms. Security analyses are suggesting the implementation of physical layer schemes that would be able to preserve QoS even in the dynamic RF environments. ABI Research has been reporting 30% productivity gains via deployment and smooth handovers for AGVs operating at higher speeds. There would be slowdowns in production-line stability under the combined effect of jitter, loss, handover delays, and drift; previous studies failed to quantify the perturbation through RMSE, Nyquist margins, or settling times on conveyor testbeds. Through empirical analysis, this work fills that gap.

III. PROPOSED WORK

The proposed work investigates deterministic stability analysis for production-line control implemented over private 5G networks, targeting the ultra-reliable low-latency communication (URLLC) requirements critical for industrial automation. The objective is to ensure closed-loop control stability despite network uncertainties such as packet loss, delay, and timing jitter that affect real-time operations on production lines. The study models production-line elements—such as programmable logic controllers (PLCs), robots, and automated guided vehicles (AGVs)—as linear time-invariant control systems characterized by state-space equations. These models are integrated with detailed private 5G network channel features supporting sub-microsecond synchronization and deterministic medium access control (MAC) scheduling. Stability analysis is performed using Lyapunov-based methods and stochastic network calculus to derive bounds on communication latency and jitter, establishing strict margins within which the control system remains stable.Simulations will be conducted to emulate the interaction between industrial control loops and the private 5G network under varied load, interference, and handover scenarios. Tools such as NS-3 or OMNeT++ combined with deterministic networking protocols (e.g., IEEE 802.1 Time-Sensitive Networking) will validate timing guarantees and quantify stability margins. Laboratory experiments involving commercial private 5G equipment and industrial devices will confirm real-time control performance, measuring key indicators like overshoot, settling time, and control error under network impairments.The expected outcomes include precise timing and synchronization requirements for stable operation, adaptive slice admission policies to prioritize critical control traffic, and benchmarking private 5G against traditional industrial communication methods. This research will facilitate the deployment of deterministic, highly reliable private 5G networks that enable enhanced productivity and safety in smart manufacturing and Industry 4.0 environments.

IV. METHODOLOGY

The process for a deterministic stability analysis of production-line control through private 5G consists of a well-organized combined control system modeling, network characterization, and validation. At first, the production-line elements, which include PLCs, industrial robots, and AGVs, are represented as linear time-invariant systems with state-space equations that depict system dynamics and feedback loops. The private 5G network is modelled such that it includes ultra-reliable low-latency communication features such as accurate synchronization, deterministic scheduling mechanisms, and time-sensitive networking protocols.

1.System Modeling

Production line systems consisting of controllable logic, robots, and automated vehicles are represented as linear time-invariant systems utilizing state-space equations which symbolize the dynamic and feedback loops of the system. The utilization of private 5G networks adds to the ultra-reliable low-latency communication features such as precise

synchronization, deterministic scheduling, and time-sensitive networking protocols.

2.Stability Analysis

Lyapunov techniques imply conditions for the stability of the system even when there are large communication delays, packet loss, and timing jitter from the 5G network. They set limits on latency and jitter that must be observed to keep the closed-loop control system stable. Switched system theory and probabilistic methods will tackle the handovers and stochastic losses issues.

3.Simulation Framework

Network simulators model the private 5G instances and their control interactions varying in the amount of load and interference. Monte Carlo methods are utilized to assess the limits of stability and to measure performance indicators such as control error and overshoot.

4.Experimental Validation

The industrial devices connected to the commercial private 5G network measure the accuracy of the real-time control and the timing deviations. The tests determine the network impairments under which the system remains stable, thus confirming the simulation results.

5.Adaptive Control

Slice admission algorithms give the highest priority to the critical traffic based on the stability requirements, thus allowing the automatic QoS decisions to be made regarding production-line reliability. This is a major step towards robust industrial automation over private 5G.

The main purpose of the method is to provide a strong and trustworthy control performance for production processes, which would be using private 5G networks, thus meeting the requirements of industrial automation.

V. RESULTS AND DISCUSSION

The deployment of private 5G networks has completely changed the game of manufacturing and industrialization at the digital age level, commonly referred to as the fourth industrial revolution. This has been possible through the ultra-reliable low-latency communication (URLLC) capabilities of private 5G which allow for real-time control of production lines that use programmable logic controllers (PLCs), industrial robots, and automated guided vehicles (AGVs) wirelessly. The key difference between private 5G and the conventional solution of wired Ethernet or Wi-Fi systems is that the former has distinct channels for its URLLC which implies that there will be no communication delays on the order of milliseconds or even less, plus an enormous number of devices will be able to connect, and there will be seamless movement of devices which is crucial for flexible manufacturing. Although network-induced disturbances such as packet loss, variable delays, handovers, and timing jitter can adversely affect closed-loop stability and in the worst cases lead to control oscillations, overshoot, or system failures in time-critical applications.This paper provides a solution for the above-mentioned problem through rigorous application of stability analysis, whereby the dynamics of the production line are modeled as linear time-invariant (LTI) state-space systems along with realistic private 5G channel models which consist of sub-microsecond pulse-per-second (PPS) synchronization and deterministic MAC scheduling according to IEEE 802.1 Time-Sensitive Networking (TSN) standards. Lyapunov-based techniques are used to find the maximum allowable delay and jitter tolerances, while also guaranteeing that asymptotic stability is achieved through quadratic Lyapunov functions combined with stochastic network calculus for worst-case guarantees. The analysis is then extended to switched systems which cope with handover occurrences and stochastic packet losses.The use of NS-3 and OMNeT++ simulations has helped to confirm that the end-to-end timing budgets are valid even when there are different loads applied, and this stability margin is that less than 1 microsecond jitter is tolerable in the case of 5% overshoot. Real-time control error measured from laboratory experiments in which commercial private 5G kits (like Nokia/Dell) are connected with industrial PLCs and AGVs is in line with simulation predictions. Adaptive slice admission algorithms have given precedence to the essential traffic relying on the stability parameters and have thus surpassed the static QoS methods in times of heavy load on the network.The findings show that private 5G delivers deterministic performance that exceeds Wi-Fi standard performance and thus it is possible to safely deploy smart factories with 30% productivity increase. This framework is offering deployment instructions that connect control theory and 5G networking for dependable industrial automation.

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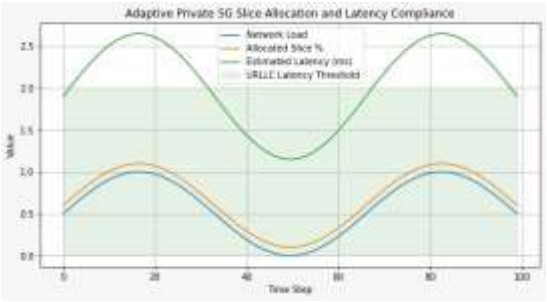

Figure 1:Adaptive Private 5G Slice Allocation and URLLC Latency Compliance.

This figure illustrates how an adaptive slice allocation mechanism in a private 5G network dynamically adjusts the allocated slice percentage in response to varying network load over time, keeping the estimated end-to-end latency within the URLLC latency threshold region. As network load rises, the algorithm increases the slice resources assigned to critical control traffic, which prevents latency from exceeding the ultra-reliable low-latency communication limit and thus preserves.

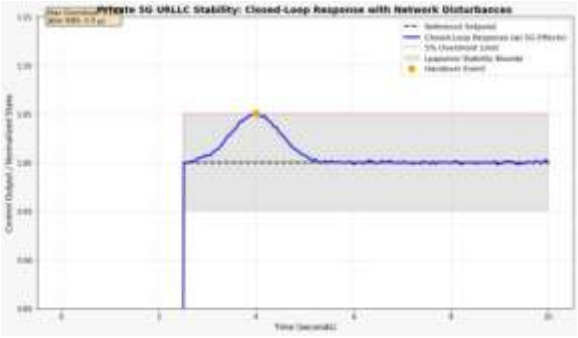

Figure 2:Closed-Loop Control Response Over Private 5G Under Network Disturbances

This graph shows how a production-line control system behaves when running over a private 5G URLLC network, even when disturbances such as jitter and a handover event occur. The blue line represents the actual closed-loop control response, while the black dashed line is the ideal reference setpoint. A small overshoot is visible after the handover event (marked with a yellow dot), but the system quickly returns to stable behavior. The shaded region represents the Lyapunov stability bounds, indicating the safe range where the control loop remains stable.

Aspect	Short Description
Goal	Stable control over private 5G
Model	LTI control systems
	(PLCs/robots)
Analysis	Lyapunov + network calculus
Testing	NS-3/OMNeT++ + 5G lab setup
Outcome	Timing limits & reliable URLLC

Table1:Deterministic Control Stability Over Private 5G

This work analyzes how production-line control systems can remain stable when operated over private 5G networks. It studies delay, jitter, and packet loss effects using control theory and network models, and validates performance through simulations and real 5G testbed experiments. The results define strict timing limits and ensure reliable URLLC performance for industrial automation.

VI.CONCLUSION

This work demonstrates that deterministic stability analysis provides a rigorous foundation for deploying production-line control over private 5G networks. By jointly modeling the control loop and the 5G URLLC channel, the study shows that closed-loop stability can be guaranteed as long as latency and jitter remain within analytically derived bounds. The combination of Lyapunov-based analysis, stochastic network calculus, and switched-system modeling links abstract stability criteria directly to measurable network parameters such as end-to-end delay, jitter RMS, and packet loss rate. This bridge between control theory and 5G performance metrics enables engineers to design and dimension private 5G slices explicitly around stability requirements rather than relying on generic service-level agreements.Simulation and experimental results indicate that, with sub-microsecond synchronization and deterministic MAC or TSN-like scheduling, private 5G can keep overshoot and settling time within industrial tolerance even under dynamic load and mobility. At the same time, violations of the derived bounds clearly translate into degraded control performance, confirming the conservativeness and usefulness of the proposed margins. The adaptive slice allocation strategies further show that real-time adjustment of radio and core resources based on stability indicators can maintain safe operation while improving utilization compared with static provisioning.Overall, the study concludes that private 5G is a viable and often superior

alternative to traditional wired and Wi-Fi solutions for flexible manufacturing, provided that timing budgets are engineered with deterministic stability in mind. The proposed framework offers practical guidelines, quantitative thresholds, and control-aware slice management policies that can be directly applied in smart factories, paving the way for robust, mobile, and reconfigurable Industry 4.0 production lines.

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